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Durability of Oxygen Sensors

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Ann Arbor, MI

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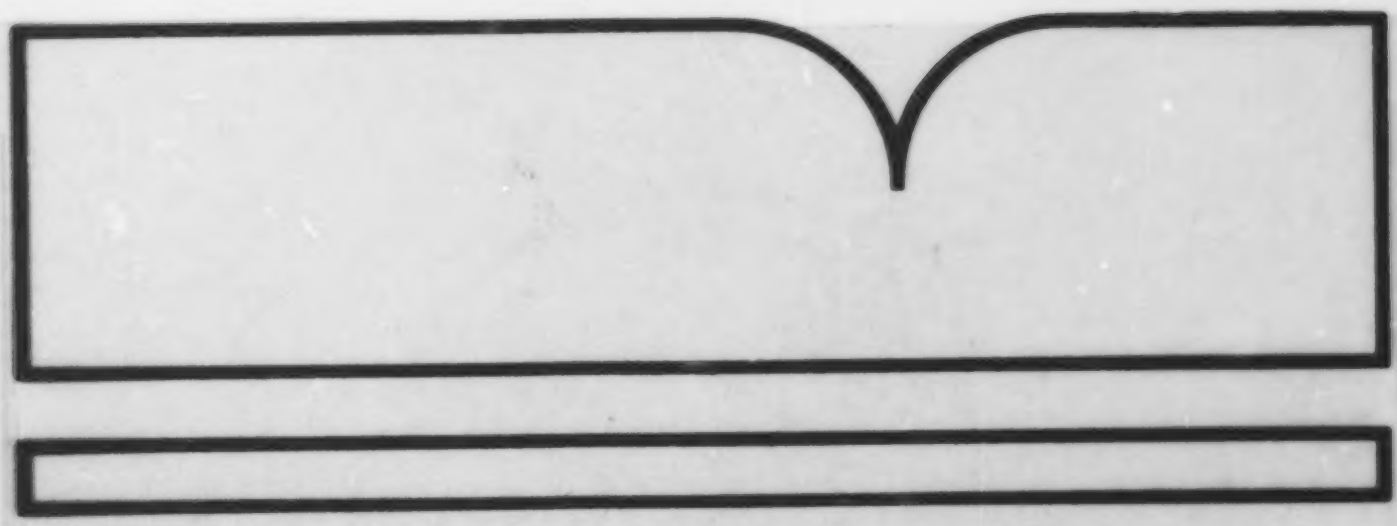

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Technical Report

Durability of Oxygen Sensors

By

Lisa Snapp

March 1985

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16. ABSTRACT

This report describes the results of dynamometer and vehicle durability testing from a variety of sources, as well as common causes of failures for oxygen sensors. The data indicates that oxygen sensors show low failure rates, even at mileages of 80,000 miles and beyond.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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I. Introduction and Summary of Comments

As emission requirements continue to tighten, new emission control technology is constantly being developed. This technology must result in equipment which is not only initially effective, but also durable. One important aspect of durability is the amount of maintenance required. Despite auto manufacturers' maintenance schedules for warranty requirements, many consumers do not maintain their cars at recommended mileage intervals. This is especially true if no problem is apparent to the driver who fails to do the maintenance. The longer the affected equipment lasts without maintenance, then, the better the emission control will be in use.

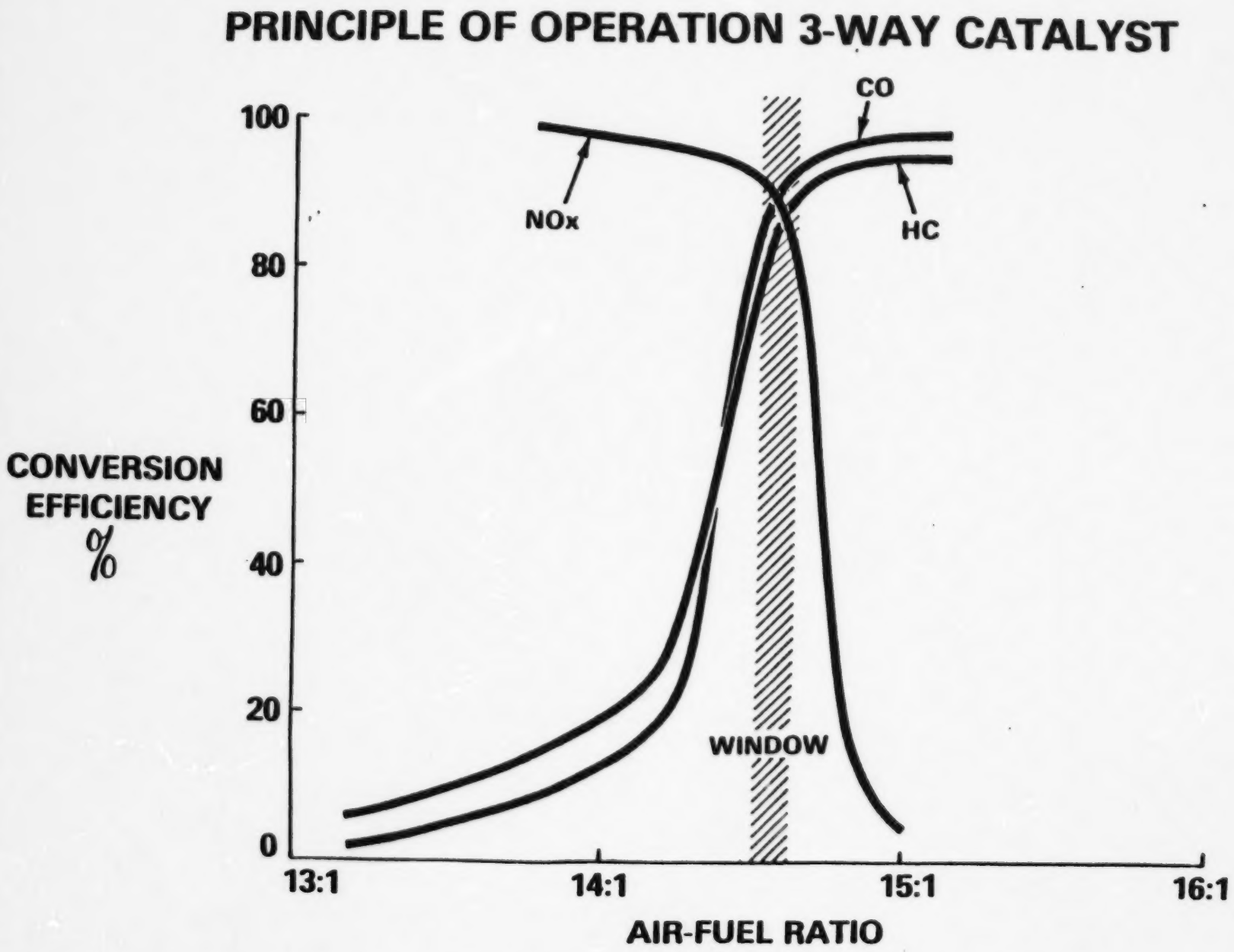
The oxygen sensor is such a piece of equipment. Some manufacturers suggest replacement at 30,000 (30K) miles, while most suggest 50K for model year 1984 vehicles.[1] If the life of the sensors could be extended to higher mileage, emissions could be significantly reduced. In light of this, oxygen sensors were included in the recent EPA proposal to extend maintenance intervals to 100K for emission-related components.[2]

In response to EPA's proposal, most manufacturers of gasoline-fueled engines submitted comments which opposed the extended interval. These manufacturers argued that the maintenance interval should not be extended beyond the 30-50K range. Their position was based on the claim that no data existed to support the feasibility of 100K durability for oxygen sensors. Manufacturers did not present factual information indicating a lack of high-mileage durability for oxygen sensors. Rather, they indicated that it was unknown whether or not a 100K interval was feasible. It is the purpose of this report to discuss the technological feasibility of such an extension for the oxygen sensor and evaluate any data available on high-mileage performance of oxygen sensors.

II. Background

Oxygen sensors have been widely used since model year 1981 in conjunction with three-way catalysts (TWC). The sensors give feed-back control of oxygen partial pressure in the exhaust to an electronic control module (ECM), in order to keep the air/fuel (A/F) ratio in a narrow range near stoichiometry. Figure 1 shows this range, which gives maximum conversion efficiency of HC, CO and NOx emissions, as well as high fuel economy.[3] Two types of sensors have so far been developed: a galvanic zirconia sensor and a resistive titania sensor.[4] The zirconia sensor has virtually the entire market, but this is probably due to its timelier development rather than any inherent technical advantage. Some manufacturers are looking into titania sensors for 1986 or later model years.

Figure 1


PRINCIPLE OF OPERATION 3-WAY CATALYST
CO
NOx
HC
100
80
60
40
20
0
CONVERSION EFFICIENCY %
WINDOW
13:1
14:1
15:1
16:1
AIR-FUEL RATIO

The popular zirconia sensor is shaped like a thimble of zirconia ceramic, coated with a noble metal. The open end of the thimble points out of the exhaust flow, as can be seen in Figure 2.[3] The inner, reference surface works like an anode, ionizing the oxygen of the atmosphere. The outer surface acts as a cathode, combining carbon monoxide from the exhaust with oxygen ions. The relative rates of the two reactions can be combined in the Nernst equation to determine the voltage produced:

$$E = \frac{kT}{2e} \ln [PO_2(atm)/PO_2(exh)]$$

Where:

E = the potential difference,

k = the Boltzmann constant,

T = temperature in degrees kelvin,

e = the electronic charge,

$PO_2(atm)$ = the atmospheric oxygen partial pressure, and

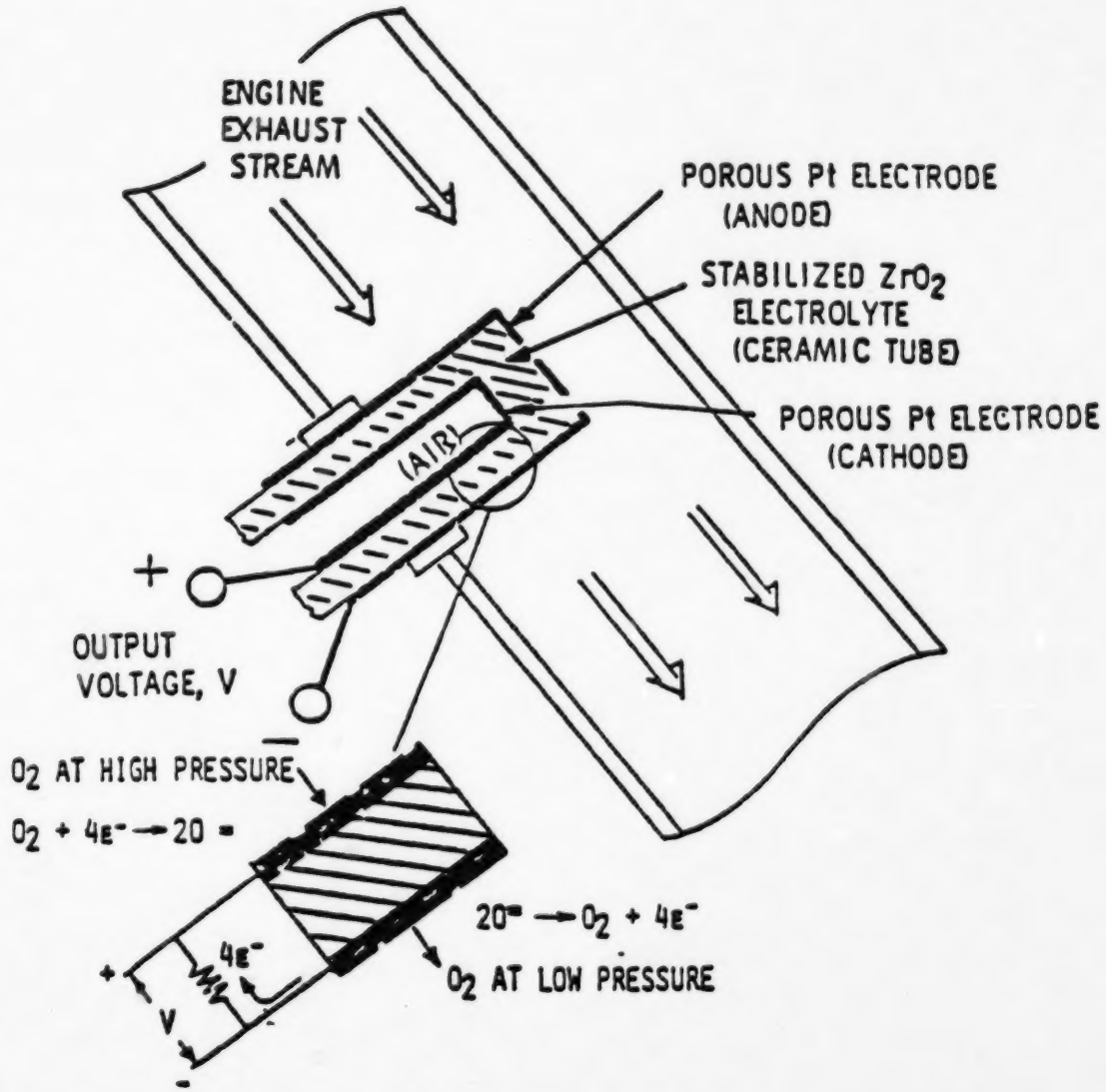
$PO_2(exh)$ = the exhaust oxygen partial pressure.[3]

A lean A/F ratio, with low carbon monoxide and relatively high oxygen partial pressure in the exhaust, gives a low voltage reading. A rich A/F ratio, conversely, gives a high voltage reading. The voltage change indicating a rich/lean change occurs as a step near stoichiometry, as in Figure 3.[3] This voltage information is fed to the ECM, which alters the air/fuel ratio in order to maintain a value near stoichiometry. Thus, a switching action from rich to lean and back constantly occurs.[3]

The same switching action takes place with the titania sensor, but it is a semiconductor rather than an electrolytic material. Oxygen vacancies in the crystal lattice form with rich A/F ratios, and are replaced when the mixture is lean. During rich operation, electrons are donated into the conduction band, and resistance is low compared to that in the lean state, which has few donor electrons. A voltage divider network utilizes these extreme resistances, as well as the ideal, which is midway between the logarithmic lean and rich resistance values. Voltage output is then similar to that of the zirconia sensor: low for lean A/F ratios and high for rich. The same switching response maintaining A/F ratio near stoichiometry occurs, controlled by the ECM.[4]

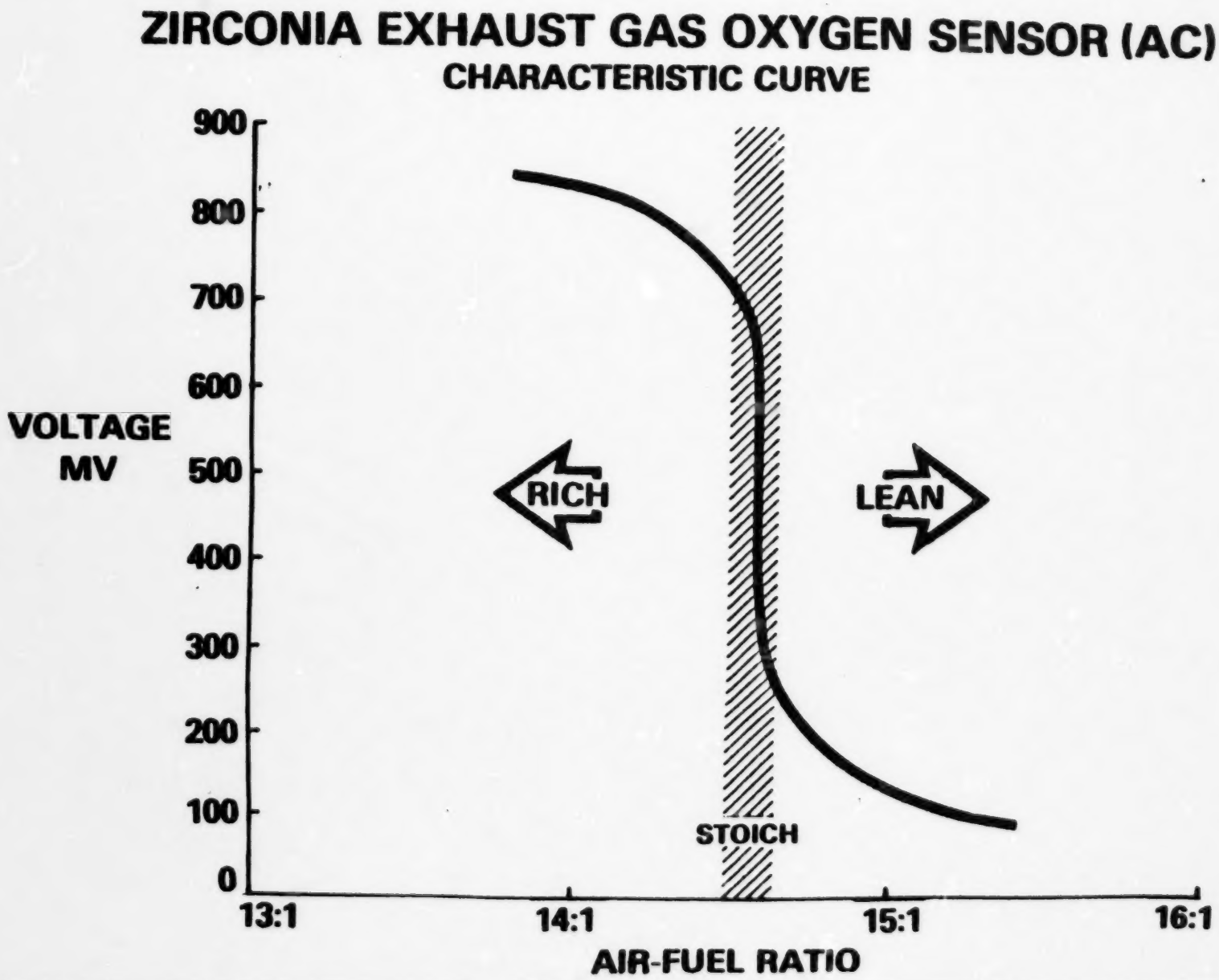
Figure 2

SCHEMATIC - ZIRCONIA SENSOR



NERNST EQUATION: $V = (RT/4F) \ln (pO_2 \text{ AIR}/pO_2 \text{ EXH.})$

Figure 3


ZIRCONIA EXHAUST GAS OXYGEN SENSOR (AC)
CHARACTERISTIC CURVE
VOLTAGE
MV
900
800
700
600
500
400
300
200
100
0
RICH
LEAN
STOICH
13:1
14:1
15:1
16:1
AIR-FUEL RATIO

Upon failure of the oxygen sensor, the ECM defaults to a preselected condition. In most cases, the default is to full rich operation. This strategy ensures driveability of the car. However, the driver cannot tell that anything is malfunctioning; meanwhile, emissions increase greatly. Warning lights are installed in some models to warn the driver when the oxygen sensor has failed or when it is time for its scheduled maintenance. However, some drivers will not heed the lights, and will thus allow high emissions to continue. Some models default to stoichiometry, which is a preferred default from the emissions standpoint. This cannot, however, keep emissions as low as can the feedback loop with the sensor. It is also possible to set the default to lean, but as this will give the car only limp home capability, manufacturers disfavor it.

Therefore, in order to keep HC, CO, and NOx emissions at a minimum, it is imperative that the oxygen sensor remain operative. Early sensors were predicted to be good at least to 15K miles. As will be explained below, current testing shows that sensors are good for at least 50K miles and perhaps far beyond that point. However, the new sensors that are beginning to reach the market, particularly heated and/or titania sensors, are being developed for reasons other than greater durability. For instance, the new heated sensors allow closed-loop operation within a few seconds of engine start-up; non-heated require open-loop until the engine temperature climbs high enough for quick sensor response. Titania sensors seem to have quicker response times than the currently used zirconia. Vendors indicate that they also may be substantially cheaper, although auto manufacturers express doubts. Development in terms of extended durability could easily take a back seat to such improved performance and cost issues. Satisfactory durability from the point of view of the auto manufacturers and their warranty requirements has already been reached. Whether this lifetime can be extended has not previously been of particular interest. It is possible that this durability can be extended to as much as 100K miles.

Such an extension of durability of oxygen sensors is important for manufacturers from a competitive point of view. The deteriorating sensor with the default to rich condition found on most models results in a significant loss of fuel economy. On the one hand, this may encourage owners to seek vehicle maintenance, thus effecting a replacement of the faulty sensor. On the other hand, it may decrease owner satisfaction with the vehicle, due either to the expense and trouble of replacing the sensor or the decreased fuel economy for those who do not seek maintenance. Thus, extended durability should also be preferable in order to maintain consumer satisfaction.

III. Sensor Failures

The causes of sensor failure have been investigated by manufacturers and vendors. One extensive study was done by the Robert Bosch GmbH, which investigated control efficiency of sensors under a variety of field operating conditions.[5] According to this and other sources, there are several causes of sensor failure: extremely high or low temperatures, large temperature gradients, leaded fuel, physical damage, and ECM malfunctions. Occurrence of these problems can be reduced, to some extent, with proper control and maintenance of the sensor and engine.

Erosion of the coating apparently takes place at very high operating temperatures (900°C at the sensor tip) over long periods of time. The outer electrode decomposes, and the protective coating flakes off. On the other hand, deposits of oil accumulate at low temperatures (500°C) and are then glazed on at intermediate temperatures (650°C). These deposits consist of phosphorous, calcium, zinc and lead. They can be reduced by controlling oil type and consumption.

Contamination of the sensor by leaded fuel is also a problem: lead contamination at low temperatures, followed by high temperature operation, creates lead deposits which cannot be removed. Lead contamination at high temperatures can be cleaned up with the subsequent use of lead-free fuel. Therefore, low operating temperatures should be avoided in order to reduce both oil deposits and lead contamination.

In order to allow higher temperature operation, high temperature ceramics have been developed. The temperature range to which the sensor is exposed can also be controlled by choice of placement in the exhaust manifold. The use of high temperature ceramics then allows placement closer to the engine, avoiding the lower temperatures which decrease lifetimes due to deposits. These ceramics can also better withstand cracking due to extreme temperature gradients.

Cracking of oxygen sensors due to external forces is difficult to prevent, as such forces are unpredictable. Occurrences of this type of physical damage are infrequent, however. Also infrequent, but serious, is malfunctioning of the ECM so as to damage the sensor. This malfunction involves a current overload to the sensor. The output voltage of the sensor under rich conditions then sinks to a low level. The voltage step is reduced to below the threshold level read by the ECM as a switch and differences between rich and lean operation are thus not registered. Of course, the ECM can also malfunction on its own, but this is not considered an oxygen sensor failure.

IV. Warranty Practices

Current warranty practices for light duty vehicles include minimum maintenance intervals of 30K and 50K miles. The 30K requirement appears to be very much on the safe side, especially in light of comments by Toyota:[6] "We are not opposed to the extension of the minimum maintenance interval to 50,000 miles. We have already adopted maintenance-free type O_2 sensor for useful life for our 1981 models." Toyota subsequently did increase their interval to 50K.

The percent of light duty vehicle families equipped with TWC which are certified with 50K maintenance schedules has been steadily increasing. For model year 1980, over 90 percent had 30K schedules; the remainder had 50K. For model year 1984, 67 percent of the light duty engine families with TWC have 50K maintenance schedules. This includes all of the domestic manufacturers, as well as some foreign automakers. It appears that there are no particular problems with a 50K warranty on oxygen sensors. This conclusion is confirmed by the test data discussed below.

V. Vendor/Manufacturer Data

Oxygen sensor vendors and auto manufacturers have done a substantial amount of testing on sensors. This testing has typically addressed aging characteristics only up to 50K in order to meet warranty requirements. Up to this mileage, the tests point to acceptable sensor performance, particularly in the most recent designs.

Early results did not promise much in the way of durability, as evidenced in a 1977 SAE paper from Bosch.[7] "A sensor lifetime of more than 25,000 km can be predicted from the results of the sensor tests . . .;" about 15,000 miles were the extent of the reliable lifetimes at that date. As use of the sensor has grown, however, assurance of its lifetime has also grown. Test vehicles have had a chance to accumulate mileage, and numerous dynamometer tests have been conducted, all indicating longer lifetimes. Sensor design itself has developed, also adding to expected durability. Current projections run to 50K and beyond.

The main thrust of durability testing has been on the dynamometer. This is due to its ease and controllability in comparison to in-use vehicle mileage accumulation. Early (1979) testing by Bendix[8] shows a gradual deterioration of sensor characteristics, particularly internal resistance, over dynamometer testing up to about 40K miles. This degradation, however, does not appear to be serious. Rich voltage stays

well above the threshold of 600mV, and response times do not drastically increase or decrease. More recent publications, particularly a customer product information booklet by GM and AC Spark Plug[9], indicate no significant degradation trends in aging sensors. These were tested using dynamometer engines on an emission test accumulation schedule, for an equivalent of 50K miles. Other dynamometer tests have compared titania to zirconia sensors. These results are very promising, indicating better performance over greater mileage for the new titania sensors relative to the zirconia type. GM shows that a titania sensor maintains stoichiometry for over 50K simulated miles on the AMA-2 dynamometer schedule.[10] Similarly, Ford reports ". . . no significant feedback system degradation in emissions as well as in fuel economy," when installing dynamometer-aged titania sensors in vehicles, and running hot and cold CVS-75 tests.[11] Bendix likewise reports titania sensors with which " . . . good engine durability has been achieved beyond the 50K or 1000 hr point."[4] For all of these titania sensors, design objectives have been to better the performance characteristics of the zirconia sensor, such as response times and voltage levels, while keeping costs down. These objectives reportedly have been achieved, with at least 50K durability being cited in all reports. As mentioned above, greater durability has not been a critical design objective.

The preferred approach to testing is mileage accumulation by in-use vehicles. In-use testing has an obvious appeal in its realism. It involves conditions critical to oxygen sensor lifetimes -- temperature extremes, potholes, flying stones, dirt, splashed water -- which don't exist in the sterile dynamometer environment. However, this approach is more difficult due to the time and expense involved, and leads necessarily to a smaller data base. The test is also less controllable, with usage patterns that aren't always known, giving data which may not be representative. In-use testing is thus used to verify that the results of dynamometer testing are representative, or to identify problems and oversights in such testing.

Bendix ran in-use testing in their 1979 study mentioned previously.[8] Three cars were each run on a highway driving pattern for 47,700 miles. This control program shows results similar to those of the dynamometer-tested sensors: "sensors are subjected to overall degradation in dynamometer or vehicle tests. The output voltage gradually decreases, the internal resistance increases, the L-R response time increases, but the R-L response time generally decreases." Bendix also conducted vehicle road durability on 13 sensors.[12] While mileage accumulation was somewhat low (12.7K), the sensor showed

excellent durability when the output voltage switching threshold was chosen to be 350 mV: "... sensor output in this range (is) extremely stable over the life of the sensor." Other in-use vehicle testing was done by GM.[13] Four vehicles were run on a 50K mile certification durability schedule. Two exceeded emission standards at 10K. Various components were replaced, including oxygen sensors, despite the fact that they were still functioning. The other two cars had maintained allowable emission levels to 50K. All of these cars had system maintenance performed as necessary, since they were development vehicles. Conclusions on the entire emission control system are therefore difficult to draw. The two cars with original oxygen sensors, however, show acceptable performance for 50K, and at that point are still well within compliance. Road testing, therefore, verifies the results of dynamometer testing: oxygen sensors generally have lifetimes of at least 50K miles. In fact, there was no indication that any of these in-use sensors were even approaching failure at this level of mileage accumulation.

For various reasons, durability data beyond 50K is scarce from these sources. Manufacturers have not had warranties beyond 50K miles; therefore, they have no information about the replacement of sensors after this point. Because of the manufacturers' lack of interest in durability beyond 50K miles, vendors have not emphasized high mileage lab testing. With the extension of useful life for LDT's, manufacturers have begun looking at durability beyond 50K miles. These programs have been started too recently, however, to have yet yielded any results.

VI. EPA Data

The EPA, however, has some in-use emissions data available which provides information on oxygen sensor failure rates above 50K. Testing involves model year 1981, 82 and 83 cars in EPA emission factors testing programs. These vehicles are recruited from their owners and emission tested. The sample used to generate this data includes 393 cars equipped with oxygen sensors. The vehicle sample encompasses a variety of domestic and foreign manufacturers and a range of sizes and accumulated mileages.

In this testing program, gross emitters receive a system performance check in order to identify reasons for excess emissions. Engine components with suspected problems are individually tested; tune-up, repair or replacement is performed as necessary. The test is then rerun. With this sequence of events, it is likely that all grossly failed components are noticed and reported. However, gross emitters

often have a variety of low performance components which contribute to the high emission level. Such generally poor performance is due to aging, misfueling, lack of maintenance, hostile environmental conditions, and/or abuse; these can affect the entire vehicle, not just one component. Hence, it is difficult to determine the emissions impact caused by the failure of any one component, such as the oxygen sensor.

It is also important to note that oxygen sensors are not strictly pass/fail devices. Some of the most common failure modes result in a gradual deterioration of performance. Sensors with such deterioration may still perform well enough to allow the car to pass emissions testing, while acting well below peak performance, and may not provoke a default response from the ECM. Such sensors would not be reported in test results so long as the vehicle passes.

The sensors which are reported in the following results were determined to be bad by a "fail" reading on an oxygen sensor tester. This tester can check the sensor operational characteristics for idle and off-idle modes, and registers a "fail" when the voltage level has dropped below the threshold which the ECM reads as a rich/lean switch. This tester is used on gross emitters in cases where the sensor is suspected, either due to engine operational characteristics or to a generally malmaintained engine. This requires some judgment and may not result in a perfect reporting of poor sensors, but probably reports all grossly failed sensors due to their crucial role in emission levels. These results, then, report grossly failed sensors in vehicles with high emission levels; these vehicles may also have other engine problems.

Results of this testing show that most in-use oxygen sensors continue functioning to very high mileages. This conclusion is based upon the assumption that the sensors in place at the time of testing are the originals; that is, that the owners haven't had the sensors replaced prior to testing. Indications from various EPA recall and surveillance programs and owner surveys are that this assumption is largely correct. When owners were questioned, most said that they ignored maintenance intervals for oxygen sensors, even when such intervals were indicated by flags or lights; in most cases for vehicles with such indicators, the flags or lights were reset without replacement of the sensors, despite the fact that replacement may have been necessary for the warranty. Owners cited the high cost of replacement and no noticeable loss in driveability or fuel economy as reasons for not following maintenance schedules. For those vehicles which also had warning lights indicating malfunctions rather than just maintenance intervals, most owners again responded that

maintenance was not performed, particularly if the light went off again before the owner could take any action. Based on these owner responses, EPA has good reason to believe that oxygen sensors are generally not replaced, and therefore that those in the testing program which generated the following data are most likely original sensors.

As can be seen in Table 1, failures accumulate with mileage at a slow rate, reaching an overall value of 3.3 percent at the highest mileages, up to 100K. This value represents the total failure rate for all cars in the sample. When this data is divided into pre- and post-50K ranges, failure rates are 1.4 percent and 9 percent, respectively. So, even high mileage sensors are performing satisfactorily for over 90 percent of the vehicles.

The 9 percent failure rate is fairly constant throughout the post 50K range, although there is some indication that it may have increased in the 80K-100K mileage group. However, the sample size in that group (8 vehicles) is too small for any final conclusion to be drawn. The failure rate for those vehicles over 70K is 9 percent.

For those cars with failed sensors, emissions far exceeded standards. The HC and CO standards were consistently exceeded: the HC by all 13 and the CO by 12 of the vehicles with failed sensors, at an average emission rate of three times the standard. NOx standards were exceeded by 5 of the 13 vehicles.

When vehicles received restorative maintenance, HC and CO emissions dropped considerably. A sample of nine gross emitters received maintenance which included the replacement of failed oxygen sensors. The HC levels dropped from four times the standard to less than twice the standard, while CO levels fell from greater than seven to one and a half times the standard. NOx emissions also showed a slight decrease, from one and a half times the standard to just slightly over it. Because of the limited sample size, the values may not be representative, but the trend is clearly toward a much more acceptable level of emissions.

However, it must be noted that these reductions are not due entirely to oxygen sensor replacement. All nine vehicles received other maintenance, including the replacement of air filters. Several also had carburetors replaced or timing adjusted. These and various other repairs all contributed to the reduction in emissions. This concurs with the idea that an oxygen sensor failure and the corresponding elevation in emission levels usually occurs not as a cataclysmic event but as a gradual deterioration. A deterioration also occurs in

Table 1

Total Oxygen Sensor Failures

Total Mileage	Total Cars	Total Failures	Total Failure Rate
Up to 10K	24	1	4.2*
20K	139	1	0.7
30K	213	1	0.5
40K	250	2	0.8
50K	293	4	1.4
60K	327	8	2.4
70K	360	10	2.8
80K	385	11	2.9
100K	393	13	3.3

* Unreliable due to small sample

other engine components, which together affect emission reduction efficiency. It is this in-use deterioration that should be slowed with improved component design in order to achieve extended lifetimes and reduce emissions.

VII. Conclusions

Most manufacturers (67%) currently specify maintenance for oxygen sensors at 50K and durability to this mileage is well supported by EPA data, manufacturer comments, and technical literature. According to in-use test data, the majority of oxygen sensors currently in use perform satisfactorily to even higher mileages, in the range of 80K. This is despite the fact that sensor manufacturers have not yet expended many resources to extend durability beyond current maintenance practices. The data available at the present time are inconclusive about sensor performance beyond 80K, but seem to indicate an increasing risk of failure. Therefore, it is appropriate to revise the 100K allowable maintenance interval originally proposed for oxygen sensors downward to 80K.

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